FEASIBILITY AND PROBLEMS OF TLS IN MODELING ROCK FACES FOR HAZARD MAPPING

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ABSTRACT:
In the paper we focus on the application of TLS to carry out the geometric surveying of rock faces to derive their DSM for simulating possible paths of falling rocks and then drawing hazard maps. After a general overview about the state-of-the-art of laser scanning tecniques applied to geological field, some operational addresses to people interested in this specific application are given. On the opinion of the author, the surveying of rock faces is one of the tasks which has taken major advantage by the appearance of TLSs, because they allow to get a DSM in a shorter time and with higher accuracy and resolution with respect to other topographic and photogrammetric methods, considering the degree of automation as well. In the second part of the paper three real experiences recently carried out in the Italian Prealps are presented. Each of them would like to give to the community the workflow of the application itself, so that practitioners could be apply the same method in their practical cases. However, main drawbacks are underlined and some guidelines for further developements proposed.

1. INTRODUCTION

Although surveying techniques have always played a primary role in engineering geology, recently new instruments and methods for data capture and processing have introduced the chance to increase the mass and the variety of achievable information. Nowadays real-time monitoring systems based on robotic total stations and GPS, digital photogrammetric techniques, high resolution satellite imagery, satellite, airborne and ground-based InSAR methods, airborne LIDAR sensors and *terrestrial laser scanners* (TLS) devices are able to give to geologists a set of powerful tools for the geometric surveying and modeling of the sites interested by disease phaenomena.
In particular this paper is focused on the use of TLS technique, which has been pushed up in the latest years by the diffusion of the so called *long range* instruments, capable of measuring points as far as a few hundred meter from the instrument stand-point to the site to be studied. Several tests and applications have been carried out by worldwide research groups, involving either data acquisition for geometric modeling, for analysis of rock structures (Slob *et al.*, 2005), for evaluation of changes before, during and after a landslide movement (Rowlands *et al.*, 2003; Bitelli *et al*., 2004; Hsiao *et al.*, 2004) and for monitoring purposes (Biasion *et al.*, 2004; Rosser *et al.*, 2004) .
Even though the most of experiences in literature present really interesting aspects and useful considerations for planning new applications, the lack of a methodic and complete analysis about the use of TLS in the geological field is still an open problem. Furthermore, an efficient application of this technique would require a close cooperation between surveyors and geologists, which is essential to acquire very useful datasets.
Here we would like to give an address about which kinds of applications can be actually considered as fully operational and which should be better focused in future investigations. Broadly speaking, when a surface must be surveyed with an accuracy in 3D point measurement as far as 10^{-4} (i.e. 10÷20 mm at 100 m), current techniques and instruments are completely suitable to match all requirements. This class refers to a large group of applications aimed to the acquisition of the geometric surveying of a slope or face to derive a DSM for one of the purposes among the following ones:

1. support to static modelling (e.g. by finite-element methods or similar);
2. design of defence works;
3. analysis of the mophological rock structure (inclinations, discontinuities, ...);
4. simulation of possible paths of falling rocks for hazard mapping.

The second class of applications concerns those for *monitoring*. Unlike classical surveying methods allowing the high accuracy measurement of a small number of control points, laser scanning captures complete surfaces that can be compared between different times to find displacements. Two open problems still exist. First, if meaningful displacements are reduced to few cm or under, such as happens in vertical rock faces, the noise in the data set could make them unrecognizable. Secondly, a comparison between different surfaces has to be done in order to detect phisycal movements. In many cases, if a reference plane can be selected for a given area, analysis of displacements can be done by simply evaluating the variation of volume inside the surfaces. However, the problem of which kind of interpolation method should be used is open. In other cases, when movements may be limited to small portions of the slope, the detection of displacements must be performed by looking for corresponding features in two or more point clouds and by measuring displacement vectors between them.
In the following of the paper we would like to focus on the application for geometric surveying of rock faces to derive their DSM for simulating possible paths of falling rocks. Thank to this analysis, a hazard map describing areas that could be hit by rocks can be drawn. In particular, the purpose of the paper is to give an operational address to people interested in this application through the presentation of three experiences recently carried out in the Italian Prealps. Each of them would like to give to the community the workflow of the application itself, so that practitioners could apply the same method in their practical cases.
Concerning a general background on the main subject of the paper and a comparison to others surveying techniques, we refer to the work already published in Scaioni *et al.* (2004) and Giussani & Scaioni (2004), being however some basic guidelines resumed in the following paragraph.

2. A METHODOLOGY FOR TLS SURVEYING OF A ROCK FACE

Two main reasons make TLS very competitive to acquire a DSM for rock fall simulation with respect to other topographic and photogrammetric techniques: the capability to capture a huge number of points in a short time; the accuracy and resolution needed for falling rock simulation purpose, which can be completely satisfied by the current TLS technology.
First of all, the planning of a laser scanning survey of a rock face requires the definition of the following preliminary items:

1. accuracy and resolution of the required point cloud;
2. extension of the interested area and positions where scanner might be placed;
3. the TLS to be used.

Very often the survey planning is carried out by an empirical approach, based on the direct experience of surveyors on the basis of a preliminary visit on site. In Giussani & Scaioni (2004) a standard design method is proposed, defining the positions of TLS stations so that the whole object coverage at requested spatial resolution and accuracy would be guaranteed. A strong constraint is represented by the local terrain morphology, which bounds the positioning of the scanner only to the so called "available area". In all practical applications carried out by the authors, this is resulted as one of the most critical aspects to be considered, especially in mountain areas.
A very important element that is easily under-estimated at planning stage is to make a rough prevision of the amount of data to collect. One of the main open problems in today's laser scanning data processing is dealing with very huge point-clouds. In theory, a resampling of each scan could be performed after the data acquisition, but practically some SWs do not allow to do this without altering the data structure. The most part of laser scanning data processing SWs exploit the topology between points in each scan, that is derived from the acquisition along a spherical grid. All tasks involved in the process of surface reconstruction rely on this data structure, meaning that if this is altered, the surface cannot be generated. Then we could state that "trying to capture some more data as possible and than to use only those are really needed" is in general false.
The next aspect that is to be decided is the strategy for georeferencing all scans. Two different approaches are mainly followed:

- *fully GCP based registration*;
- *pairwise co-registration*: starting from a scan which is chosen as reference, all other scans sharing a sufficient number of *tie points* (TPs) are registered to a common reference system, as far as the whole block is oriented. Instead of using TPs, pairwise co-registration can be done by means of an algorithm for *surface matching*. Finally, thank to a small set of GCPs distributed in the total point cloud, this can be georeferenced to the *ground reference system* (GRS).

The use of *pairwise registration* methods is of great operational interest, because it reduces the number of GCPs to position. Unfortunately, a suitable overlap between adjacent scans is needed, which may be difficult to be guaranteed in mountain areas. According to these considerations, the registration method completely based on GCPs appears as the only which yields a sufficient accuracy in the most part of surveys for geological investigations. The materialization of GCPs may be done in different ways, being however the use of *retro-reflective* targets the most operational because they can be automatically detected and measured in each scan. The FoVs (horizontal and vertical) of the TLS will define the strategy to distrubute targets. If a *camera-like* scanner is used, targets must be concentrated inside the narrow scanned window (this topic has been accurately investigated by Gordon & Lichti, 2004). This task might become very difficult or impossible in case of a rock face (see e.g. the cases study 1 and 3 presented at par. 3). On the contrary, the use of a laser scanning featuring a horizontal *panoramic* FoV allows to put some GCPs also around the stand-points, in positions far from the surveyed area where topographic measurement can be carried out in easier way and the geometry of ground constraints improved. Similar considerations should be done for vertical FoV.
For the sake of completeness, some TLS allow to be directly georeferenced without the need of GCPs, but the accuracy that can be reach in point cloud measurement is worse than that achievable by a GPC-based method (see Lichti & Gordon, 2004; Scaioni, 2005).
Acquisition of *digital images* can be carried out during the range data capture, in order to add up information about the color texture of objects. This possibility is very important in case of rock faces presenting vegetation, which introduces noise in the DSM; color information may help in noise removal. A digital camera may be fixed to the TLS or may be used independently: in the former case, the image geometry of the camera can be related to that of the scanner, so that a corrispondence between each point of the 3D-view and the image can be established by calibration. In the latter case, each image can be oriented in post-processing with respect to the point-cloud by applying a *space resection* method. In both cases, image registration to the point cloud is performed by manually measuring well identifiable points on 3D-view and images. The *a priori* knowledge of intrinsic camera calibration parameters would reduce the number of control points to adopt.
A further interesting possibility is to integrate laser scanner data to thermal imagery, in order to texture the DSM with temperatures (see Gianinetto *et al.*, 2005).
Data processing is based on three main stages, which are performed by devoted SWs:

1. pre-editing of each scan, i.e. resampling of scans in case they are too dense and measurement of GCPs; cleaning of points located in not interesting parts, in order to reduce the total amount of data;
2. registration of all scans to a given GRS; after this task, large portions of the point-cloud may be made up by the overlap of more scans. Thank to a filtering method, duplicate data should be eliminated;
3. interpolation of the point-cloud to derive the final DSM; thank to *meshing*, the set of raw 3D points is converted into a surface; the widespread used technique is *triangulation*.

Once the desired DSM has been achieved, the simulation process of the falling rock paths can be afforded. Moreover, some by-products might be yielded from the same dataset, such as cross-sections and countour line maps, orthophotos, and in general topographic maps of the interested site.

3. THREE APPLICATIONS

The core of this paper is to present some practical applications recently carried out by the research group of the authors. From

their analysis, several aspects can be focused and some guidelines and suggestions for practitioners can be derived.
The geographic area where these case studies are localized is that of Italian Prealps, at the side of three important lakes (Verbano, Ceresio amd Lario). Main characteristics of each site are reported in Table 1.

3.1 Laveno Mombello

3.1.1 Site description: The object of this study is located in Laveno Mombello, a village at the side of Lake "Maggiore" (Verbano). The rock face at the origin of the rock fall takes place along the southern side of Sasso del Ferro (see Fig. 1). As can be seen in the map reported in Figure 2, this face is just over the inhabitated centre and it is threatening all the below area because of the possibility of rocky mass detachment.
There are a lot of destabilising elements that can act simultaneously, being lithology and position of strata the main causes of the problem. A high level of erosion of limestone strata (calcium-rich clay stratified limestones with little strata of flint) supports the formation of jutting roofs which could suddendly fall down. Different kinds of discontinuity divide the rocky mass into blocks from 0.5 till 2.5 m^3, so that there is a possibility of planar or wedge slipping. Also the arboreous and the shrubbing vegetation with the frost-thaw process contributes to worsen the instability. It would result of great interest to evaluate the stability of the slope below the face in order to get more information about mass trajectory. The side on the basis has a great inclination and debris deposits are stray blocks of different sizes, which could be pushed down by a mass falling from the superior rock face.

3.1.2 Surveying operations: The goal of the data capture is to derive a DSM for the simulation of falling down mass trajectory. To this aim, a DSM featuring a point density of 10x10 cm was required by geologists.
The instrument used for the acquisition is a profile scanner Rigel LPM-800 HA (Fig. 7), capable to acquire data at a range of about 800 m if the surveyed object has a reflectivity major than 80%. Performances and technical features are reported in Table 2. A Canon EOS 300D digital camera (6.0 Mpixels) is mounted in a stable position over the TLS, with known orientation into the *intrinsic reference system* (IRS) of the scanner. The data acquision is controlled via a PC. The energy supply of all tools is guaranteed by a Honda EU10i portable electric generator, capable of 0.9 kw allocated power with a total weight about 13 kg.
The slope presents two problems that can decrease the quality and the completeness of the survey. The first is the presence of tall trunk vegetation on the basis of the instable slope (but this is also a useful obstacle for the mass's rolling), which prevents to survey the lowest part. However, this problem is not imputable to the laser scanning technique itself, because the same difficulties would have arised by using another surveying method as well. The second problem is the presence of little shrubbery and bush on the slope. The instrument obtains the distance of the bush and not the correct distance of the underlying rock face. To avoid this problem, the execution of the survey during winter season would have been better, but the committement could not wait and we operated in June 2004.
Only one scan has been captured because of the impossibility to have a stand-point on the ground that offers the visibility of the whole rock face (see the geometric layout in Fig. 2). To avoid this problem, the laser scanner has been stationed on a terrace roof in front of the rock face. The access to the slope to put on some targets has not been possible, so that 5 GCPs have been positioned in the area surrounding the TLS at different distance and heights from it, exploiting this way the panoramic horizontal FoV of Riegl LPM-800HA and its large vertical FoV. The measurement of target coordinates has been executed by a total station Leica TCA2003, while the connection to the national geodetic network IGM95 has been perfomed by means of 3 GPS baselines. By this way, the TLS surveying could be inserted into technical maps of the same area. Only one scan has resulted sufficient to derive the needed DSM.

3.1.3 Property of the derived DSM: The acquired point-density has been about one point every 8 cm in the less favourable positions; elsewhere the point density has been even better. This resolution has been suitable for the simulation of falling rock paths, considering that the used software ROTOMAP could only deal with a reduced number of points in comparison to the total number of acquired points. As mentioned above, the point cloud describing the rock surface lacks of some portions due to three main reasons:

1. holes due to hidden sides of the face which could not be scanned from the stand-point TLS position;
2. holes due to areas where vegetation has been scanned and then removed;
3. the impossibility of surveying the bottom part of the rock face.

For items (1) and (2), holes has been fullfilled by interpolation of nearest points. In the third case, data have been supplied by a DSM derived from a digital map at scale 1:2000 of the interested area.
Once the point-cloud has been registered to the GRS and integrated in its poorly defined areas, it has been imported into the commercial software Golden Surfer in order to interpolate the DSM. Despite of problems previously addressed, the final DSM has been much more accurated than that could be straight-forward derived by available digital maps. Nevertheless, the use of manual measurement of surface points by means of a reflector-less total station did not allow to get a better final product, considering that this method would have required much more times to be accomplished.

3.1.4 Generation of the hazard map: The DMS has been used for two purposes. The first one has consisted in defining all positions where mass detachment might happen, by looking at the rock structure; in this task the integration of colour digital imagery to the point cloud has been very helpful. The second one in the determination of the trajectory of each possible falling mass by using the devoted software ROTOMAP (GEO&SOFTINT., 2004). Finally the dangerousness of the rock face has been evaluated by a particular methodology developed by the Geology and Hydrology Department of Regione Lombardia for a little dimension collapse (less than 1000 m^3). The final product is a hazard map where the area below the rock face has been classified into 5 categories, according to the quoted specifications. Colours correspond to a given probability to be hit by a falling down rock, from the higher (red) to the lower (cyan).

Fig. 1 – Image of the rock face in Laveno Mombello (Sasso del Ferro)

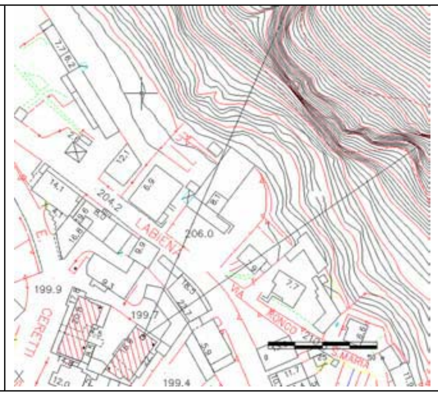

Fig. 2 – Topographic map (1:2000 scale) of the site, with positions of TLS and targets (black points)

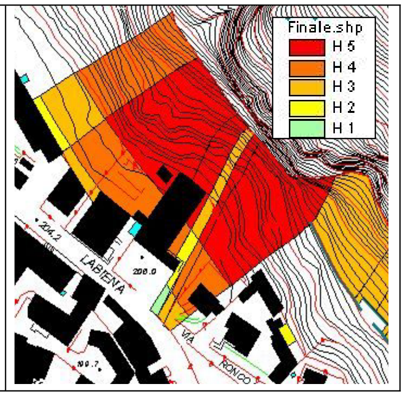

Fig. 3 – The derived hazard map

Sites		***Laveno Mombello***	***Porto Ceresio***	***Fiumelatte di Varenna***
Size of the rock face (L×H)		60×40 m	100×30 m	600×400 m
# scans		1	4	3
GCPs	**per scan**	5	8	7
	total	5	26	21
Acquisition time [min]		52	36÷41	50 (double scan)
range TSL-rock face [m]	**mean**	127	15	290
	max	159	50	350
	min	118	7	205

Table 1 – Main features of 3 presented examples

Instrument		***Riegl LMS-Z420i***	***Riegl LPM-800HA***
range of measurement [m]	**(ρ≥80%)**	2÷800	800
	(ρ≥10%)	2÷250	10÷250
Speed of acquisition with rotating/oscilating mirror [Hz]		8k/12k	>1k
St.dev. of single range meas. [mm]		10 ± 20 p.p.m.	15 ± 20 p.p.m.
Min angular resolution [deg]		0.0025	0.009
Horiz.and vert. FoV [deg]		360x80	360x160
Laser beam-width at 100 m [mm]		25	130
Size [mm]		463×210 (H×Diam)	287×300×320 (L×W×H)
Weight [kg]		14,5	15
Picture			

Table 2 – Technical features of laser scanners adopted in the presented examples

3.2 Porto Ceresio

3.2.1 Site description: The site is located just off the village of Porto Ceresio at the side of Lago di Lugano (Ceresio). This mountainside is near an important and frequented road joining the small towns of Ponte Tresa and Porto Ceresio. The morphology of the instable slope is very steep and it is directly facing the road (Fig. 4). The foot of the mountainside has not debris but it finishes in the lake.
Geologically the area has been formed of rock belonging to "Serie Porfirica of Varesotto". This formation has volcanic origin and it is composed by porphyry, porphrite and tuff. The mountainside has open fractures that isolates jutting out blocks, that do not have a support on the base. The pressure of the water in the fractures and the ice-defrost phenomena can aggravate the situation, which could bring down rock fall and blocks on the road. The rock face is not protected by any defense works and in the current condition the road is not safe. From these grounds the need to evaluate the real dangerousness of this site has arisen.

3.2.2 Surveying operations: The rock face presents good characteristics for the laser scanning surveying, because of large portions which are free of vegetation or where this has been removed thank to a mobile platform that has allowed to go up to 14 m over the road. Measurements have been carried out in summer for the same reason already reported at par. 3.1.2, by using the Rigel LPM-800 HA; in Fig. 7 the instrument is reported during a stationing at the lakeside of Porto Ceresio. The most critical aspect which has conditioned the laser scanning acquisition has been the immediate proximity to the lake, limiting the available area to place the instrument. This reason forced to acquire data with a very bended view; in Figure 5 a planimetry of the interested area is shown with the localization of the 4 TLS stand-points.
The mean time to acquire data was about 40' for each scanning. Considering that scans could not share large overlapping areas between them, a fully GPC based georeferencing method has been applied. Retro-reflective target (26 squares of 12x12 cm made up of highly reflective material) have been placed on the rock face starting from the road height as far as 15 m upwards.

Fig. 4 – Image of a portion of the rock face in Porto Ceresio

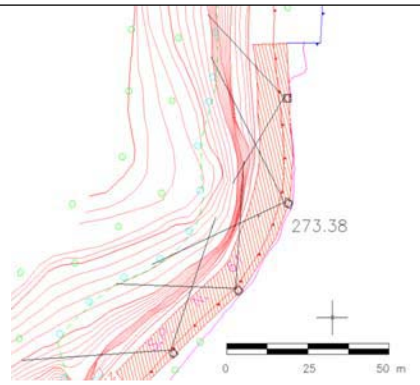

Fig. 5 – Topographic map (1:2000 scale) of the site with positions of TLS stand-points

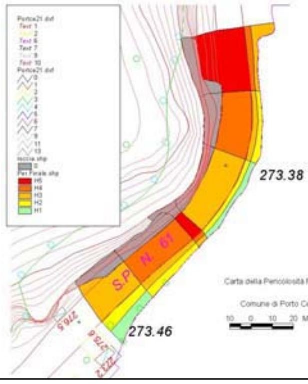

Fig. 6 – The derived hazard map

Fig. 7 - The laser scanner Riegl LPM-800 HA (on the left) during a stationing in Porto Ceresio, with the electric generator; a multi-directional target (on the right).

The use of a scanner with a panoramic horizontal FoV has suggested to position also 4 multi-directional targets (Fig. 7) outside the rock face, in order to reduce the total amount of GCPs to be measured by a total station. Multi-directional targets have been positioned at the scanner stand-points, so that each of them would appear in two or more scans. A largely redundant and geometrically good conditioned (7-8 GCPs per scan) ground constraint has been obtained by this solution. Values of sigma naugh of the l.s. roto-translation to get the registration to the GRS have resulted inferior to 2 cm for all scans. Also in Porto Ceresio the local geodetic network has been inserted in the national network IGM95 by means of GPS measurements.
However, this experience has been a character of test-field where trying different solutions, so that more efforts than those strictly needed have been carried out. This means that in practitioners applications a smaller set of GCPs (4-5 per scan) could be used without significant changes in the quality of the final results.

3.1.3 Property of the derived DSM: The resolution of the directly acquired points has been higher than one point every 10 cm, has requestes by the technical specification of the committement. This resolution has however resulted enough for the next processing steps.

3.1.4 **3.1.4 Generation of the hazard map:** Thank to the same procedure adopted for the previous example, the hazard map reported in Fig. 6 has been generated. Although the major complexity and morphology of the site, here the hazard map is quite trivial, because the rock face is sub-vertical and falling masses would follow a straight path from their original position to the road.

3.3 Fiumelatte di Varenna

3.2.1 Site description: This study is based on the observation of a rock fall that involved the village of Fiumelatte di Varenna built-up area (on the Eastern side of the lake of Como - Lario) in November 2004. In Figure 8 is reported a picture of the rock face from which rocks have felt down.
In the studied area two kinds of sedimentary triassic rocks exist: the “Calcare of Perledo-Varenna” and the “Calcare of Esino”. The first consists on black limestones with some flint nodules. These rocks are about 400 m thick on the Grigna area. Particularly in the landslide area, thinly bedding black limestones diffusely outcrop. The area is affected by some folds and faults. These sedimentary rocks are affected by close fessuration, tending to divide it into blocks, and by karst phenomena. These rocks form vertical walls where the rock fall has happened. Some joints and faults subdivide the bedrock in more or less dislocated blocks which are the intrinsic factor of the slope instability. Some debris deposits are localized on the basis of the instable slope and they show that the area is characterized by the old rock-falls and by potential future hazard.

Fig. 8 – Image of the rock face in Fiumelatte di Varenna.

3.2.2 Surveying operations: The purpose of the surveying is the acquisition of a DSM for planning of defence works as well as for the geometric and mechanical calibration of the ROTOMAP software for simulating falling rock paths. For the

measurement operation, the DSM characteristics asked for the acquisition of a surface defined by a point every 10x10 cm.
The laser scanner used for data capture has been a Riegl LMS-Z420i with a maximum operating range about 800 m when the surface offers a reflectivity superior at 80%. In a stable position over TLS, it is possible to mount a calibrated digital camera that is referenced in the intrinsic reference system of the TLS. Here a calibrated Nikon D100, equipped by a CCD sensor about 3008x2000 pixel has been mounted.
The dimensions of the slope to survey are very large: about 600 m of width and 400 m of height. The survey presented two main critical problems. Three positions have been found to perform the scanning acquisitions of different portions of the whole rock face. The adopted scanner allows the *multi-scan* option, meaning that the same points can be measured *n* times and then averaged. The time needed to acquire data has been about 50′ for each scan.
The ground georeferencing has been carried out by positioning 21 GCP materialized by retro-reflective targets. Being impossible to place them directly on the rock face, they have been positioned all around each TLS stand-point at different distances and heights. The geometric position of targets is sufficient to guarantee an accurate georeferencing of each scan by at least 7-8 ot them. Furthermore, the fact that GCPs are outside the rock face allows their use in future surveys for monitoring of displacements, activity that is currently on-going.

3.1.3 Property of the derived DSM: The resolution of the directly acquired points has been higher than one point every 10 cm, has requested by technical specifications of the committement. This resolution has however resulted enough for the next processing stages, but also in very huge point clouds, whose management has been very difficult also with high powerful computers. A solution to cope with this problem has been to divide each scan in more sub-scans, all georeferenced by means of the same set of GCPs. This solution is possible only with scanners which allow to separate the data capture from the target measurement stage, such as the Riegl LMS-Z420i does.
For this site the generation of the hazard map has not been completed yet at the moment of writing.

4. FINAL CONSIDERATIONS AND FUTURE WORK

Three examples of the use of TLS techniques for the acquisition of a DSM of a rock face with the purpose of deriving a falling rock hazard map have been proposed. These applications would like to give to practitioners some guidelines to reply similar activities in other areas.
Results obtained show somehow this surveying method is largely suitable for the requested purpose, due to several grounds: enough accuracy and point resolution, relatively short time for data capture, automation of measurement and of data processing. Moreover, some drawbacks exist, mainly related to logistic problems which happen in sites where rock faces usually are. Long range TLS are still heavy and their size cumbersome, they requires big energy supply unit (bactery or field electrical generator), a tripod for their mounting and a total station for GCP georeferencing (sometimes also GPS receivers and antennas are needed). From this point of view, some efforts should be done by vendors in order to reduce the size of laser scanners and their tools.
A further problem to focus is related the high mass of data points that are acquired in rock face surveying, which makes difficult the data processing stage also when using very powerful computing machines. Researches should be focused on two main directions. The first one concerns the optimization of the survey planning, in order to acquire only data which are really usefull; to this aim, the close cooperation with geologists is fundamental. The second one is to develop SWs able to deal with very large point-cloud and to perform all tasks involved in geometric modeling of rock faces.

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